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OF A REENTRY VEHICLE HAVING A CANTED MULTIPLE-AIR-BAG

LOAD-ALLEVIATION SYSTEM

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INVESTIGATION OF THE LANDING CHARACTERISTICS OF A REENTRY VEHICLE HAVING A CANTED MULTIPLE-AIR-BAG LOAD-ALLEVIATION SYSTEM

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SUMMARY

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An investigation has been made to determine the landing-impact characteristics of a reentry vehicle having a multiple-air-bag load-alleviation system. A 1/16-scale dynamic model having four canted air bags was tested at flight-path angles of 90° (vertical), 45°, and 27° for a parachute or paraglider vertical letdown velocity of 30 feet per second (full scale). Landings were made on concrete at attitudes ranging from -15° to 20°. The friction coefficient between the model heat shield and the concrete was approximately 0.4. An aluminum diaphragm, designed to rupture at 10.8 pounds per square inch gage, was used to maintain initial pressure in the air bags for a short time period.

Landings for an attitude range between -15° and 12° gave peak accelerations from 6 to 10.5g units, and maximum onset rates to peak accelerations of 66g per second or less. For landings made at high positive attitudes (15° and 20°), bottoming occurred and peak normal accelerations were 12 to 15g units. Horizontal velocity had little effect on landing accelerations. The landing behavior was satisfactory for all conditions tested. The canted bags were effective in overcoming the effect of the friction forces resulting from horizontal velocity. Good agreement was obtained between experimental and computed time-history acceleration curves for the 90° flight path, 0° attitude test condition.

INTRODUCTION

There has been considerable interest shown in methods for alleviating the landing loads of spacecraft when the landing is to be made on a hard surface. One method of reducing these loads involves the use of air bags. Research has been conducted on various vertical cylindrical air bags. (See refs. 1 to 3.) If, however, landings are attempted with a paraglider or a parachute operating under high horizontal wind conditions, a horizontal velocity component might become large enough to cause shear and bending deformations in the air bags. Such deformations cause the air bags to lose their stroke efficiency. The present investigation was conducted to determine the landing characteristics and accelerations of a multiple-air-bag system of canted bags designed to counteract the shear loads resulting from landings with horizontal velocities.

A 1/16-scale dynamic model of a proposed three-man spacecraft was used in the investigation. The model was tested at flight-path angles of 90° (vertical), 45°, and 27° for a vertical letdown velocity of 30 feet per second (full scale) and corresponding horizontal velocities of 0, 30, and 60 feet per second (full scale). Landings were made on a concrete surface at attitudes ranging from -15° to 20°. The friction coefficient between the model heat shield and the concrete was approximately 0.4. These tests were conducted in the Langley impacting structures facility.

APPARATUS AND PROCEDURE

A drawing of the capsule configuration is shown in figure 1. A detailed sketch of a lower air-bag mounting block is shown in figure 2. The orientations of axes, flight path, contact attitudes, and force directions are shown in figure 3. Photographs of the model are shown in figure 4. Pertinent dimensions, measured moments of inertia, velocity, and pressures are listed in table I. All values presented in this report are full scale unless otherwise indicated.

Description of Model

The model used in the investigation was a 1/16-scale dynamic model of a proposed three-man spacecraft. Figure 1 shows the general arrangement of the model with four air bags. The air bags were installed between the upper body and the heat shield.

The model was rigidly constructed of plastic-impregnated fiber glass. Lead ballast was used to bring the model to the correct weight. The model weight (27.35 pounds) simulated a full-scale weight of 7,000 pounds. In order that the air-bag pressures for both prototype and model might be the same, the weights were varied by the scale factor squared. (See table II.) The model without the air bags mounted had a moment of inertia about the pitch axis of 1,574 slug-ft^2 (full scale).

The air bags were made of two layers of thin fiber glass impregnated with latex. The warp of the fiber-glass layers was laid 45° to each other to provide shear stiffness. The bags were canted forward to counteract the shear loads resulting from landings at negative attitudes or landings with horizontal velocity. A shear strap was mounted from the front of the model to the rear of the heat shield to keep the vehicle from overrunning the heat shield at high negative impact angles or when shear loads exceeded the design loads of the air-bag system. If overrunning occurred, the air bags would bend and lose their stroke efficiency. Each air bag had a 0.159-inch-diameter (model scale) orifice, with an aluminum diaphragm designed to rupture at a blowout pressure of 10.8 pounds per square inch gage. The diaphragm maintained initial pressure in the air bags and permitted a pressure rise in order to obtain more efficient force-stroke characteristics. (See ref. 4.) Rupture of the diaphragm and subsequent pressure relief was used to prevent rebound. Details of the orifice and diaphragm are shown in figure 2. An initial pressure of 4.4 pounds per square inch gage was necessary to provide sufficient force to prevent bottoming. The initial pressures of the air bags were measured by the use of a water-filled manometer. All four bags had a common air supply line and, as a result, were vented to one another. The supply line was of such small diameter compared with the orifice diameter that its effect during impact was considered to be negligible.

The instrumentation consisted of two strain-gage accelerometers rigidly mounted near the center of gravity of the model. The accelerometers were used to measure normal and longitudinal accelerations. The accelerometers were capable of recording accelerations of ±50g units. Signals from the accelerometers were transmitted through cables to the recording equipment. The natural frequency of the accelerometers was approximately 500 cycles per second. Both accelerometers were damped to about 65 percent of critical damping. The response of the recording equipment was flat to about 135 cycles per second. Motion pictures were made to record the behavior of the model.

Test Methods

Tests of the 1/16-scale model were made at flight-path angles of 90° (vertical), 45°, and 27° at a vertical letdown velocity of 30 feet per second (full scale). Corresponding horizontal velocities were 0, 30, and 60 feet per second. Landings were made on a concrete landing surface at contact attitudes from -15° to 20°. The landing conditions simulated letdowns possible with a paraglider or parachute with variable surface winds.

Figure 5 shows the test setup used in the investigation. The horizontal velocity was obtained by a swinging pendulum. A stopping cable was used to stop the platform after a swing of one-quarter period. The sudden stop of the platform allowed the model to slip free from the model support pins and the resulting free fall was used to give the desired vertical velocity.

Computations

The computational procedure presented in reference 4 was used to obtain a computed acceleration time history of a landing from a 90° (vertical) flight path at a 0° landing attitude with the multiple-air-bag system for load alleviation. For the purpose of this paper the following assumptions were made: (1) parachute release occurred at contact and the only force causing deceleration was the gas-pressure force, (2) the air bags were inelastic and flexible, (3) the orifice discharge coefficient was 0.8, (4) the velocity at impact was 30 feet per second (full scale), and (5) blowout for all bags was simultaneous.

Scaling

When testing scale models of air-bag landing systems, it is necessary to scale air pressures unless other variables can be made to compensate for the pressures not being scaled. The scaling method used in this investigation allows the use of atmospheric pressures and requires that all air pressures be the same for both model and full-scale vehicles. The scaling method used in this investigation is such that, when pressure and acceleration are the same for the model and the full-scale vehicle, and when length varies as the scale factor, mass varies as the scale factor squared. The scaling relationships are shown in table II.

RESULTS AND DISCUSSION

A short motion-picture film supplement illustrating the results discussed in this paper has been prepared and is available on loan. A request card form and a description of the film will be found at the back of this paper, on the page immediately preceding the abstract pages.

Experimental

A tabulation of test results is given in table III. Typical oscillograph records of accelerations are shown in figures 6 and 7. Figure 6 shows that horizontal velocity has very little effect on normal and longitudinal accelerations. The maximum normal acceleration shown in figure 6 was approximately 9g units.

Figure 7 shows the effect of landing attitude on accelerations. The normal accelerations are lowest at the negative landing attitude because the slanted air bags are more nearly alined with the resultant force at the negative attitude than at the zero or positive attitudes. There is also greater possible stroke at the negative landing attitudes. The variation in longitudinal acceleration due to landing attitude is small. At landing attitudes of 15° and 20°, the two rear air bags were required to take most of the load, and because of the unfavorable direction of the resultant force, the rear bags bent forward and allowed the vehicle to strike the heat shield (bottoming) with a residual vertical velocity. In figure 7(c), the reversal in the longitudinal acceleration and the high normal acceleration are a result of bottoming.

Maximum normal accelerations for various landing attitudes and horizontal velocities are shown in figure 8. Normal accelerations were lowest for the negative landing attitudes. Landings at an attitude range from -15° to 12° gave maximum accelerations from 6 to 10.5g units. Maximum onset rate to peak acceleration, obtained by dividing peak acceleration by time to peak (table III), was 66g per second. For landings made at higher positive attitudes, 15° and 20°, (where bottoming occurred), maximum accelerations were 12 to 15g units and the maximum onset rate was approximately 100g per second.

Figure 9 shows the maximum longitudinal accelerations for various horizontal velocities plotted against landing attitude. There was a decrease in the longitudinal accelerations from 4 to 2g units as the landing attitude was varied from -15° to 12°. As would be expected, horizontal velocity had little effect on landing acceleration.

Typical sequence photographs of landings made on concrete are shown in figure 10. The model was landed at an attitude of 5° along a flight path of 27°. The vehicle overhung the rear of the heat shield during slideout; thus, the cant of the air bags was more than enough to overcome the effects of the kinetic friction forces for landing attitudes near 0°. If the coefficient of friction, between the heat shield and the landing surface, were increased or if the vehicle were landed at a slightly negative landing attitude, the vehicle would come to rest more nearly alined over the heat shield. The coefficient of friction between the fiber glass and concrete for these tests was approximately 0.4. A shear strap was mounted between the front of the model and the rear of the heat shield to serve as a safety device by absorbing the shear loads in the air bags in the event excessively high drag forces or high negative impact angles were encountered. For the conditions presented in this report, the shear strap was used only at the higher negative impact attitudes. The behavior of the multiple-air-bag landing system investigated was, in general, satisfactory.

Computations

A comparison of experimental and computed time histories of normal acceleration for a 90° flight path and a 0° landing attitude is shown in figure 11. Good agreement was obtained between computed and experimental peak accelerations. The difference in time at which peak acceleration occurs may be the result of differences in the time for blowout of each bag during the test whereas for the computed acceleration time history it was assumed that simultaneous blowout occurred in all bags.

CONCLUSIONS

Results of the landing tests of a 1/16-scale dynamic model of a spacecraft configuration having a multiple-air-bag load-alleviation system led to the following conclusions:

1. The canted multiple-air-bag landing system had satisfactory behavior for all conditions tested and was effective in overcoming the effects of the kinetic friction forces resulting from horizontal velocity.

2. Landings at an attitude range between -15° and 12° gave peak normal accelerations from 6 to 10.5g units, peak longitudinal accelerations from 2 to 4g units, and maximum onset rates to peak accelerations of 66g per second or less. For landings made at high positive attitudes (15° and 20°), bottoming occurred and peak normal accelerations were 12 to 15g units.

3. Horizontal velocity had little effect on landing accelerations.

4. Calculated acceleration-time histories were in good agreement with experimental data.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., May 6, 1963.

REFERENCES

1. McGehee, John R., and Vaughan, Victor L., Jr.: Model Investigation of the Landing Characteristics of a Reentry Spacecraft With a Vertical-Cylinder Air Bag for Load Alleviation. NASA TN D-1027, 1962.

2. Tomcsak, Stephen L.: Decelerator Bag Study. WADC TR 59-775 (Contract No. AF 33(600)-30825), U.S. Air Force, June 1960.

3. Esgar, Jack B., and Morgan, William C.: Analytical Study of Soft Landings on Gas-Filled Bags. NASA TR R-75, 1960.

4. McGehee, John R., and Hathaway, Melvin E.: Landing Characteristics of a Reentry Capsule With a Torus-Shaped Air Bag for Load Alleviation. NASA TN D-628, 1960.

TABLE I

PERTINENT VALUES FOR THE MULTIPLE-AIR-BAG REENTRY VEHICLE

	1/16-scale model	Full scale
Configuration weight, lb	27.35	7,000.0
Height, overall (air bag extended), in.	8.80	140.8
Maximum width of capsule, in.	9.18	146.9
Length of capsule, in.	7.60	121.6
Pitching moment of inertia, Y-axis, slug-ft^2	0.024	1,574.0
Rolling moment of inertia, X-axis, slug-ft^2	0.023	1,510.0
Yawing moment of inertia, Z-axis, slug-ft^2	0.04	2,625.0
Diameter of air bag, in.	2.25	36.0
Vertical height of air bag, in.	3.42	54.7
Orifice diameter of air bag, in.	0.159	2.54
Number of bags	4.0	4.0
Initial pressure in bags, lb/sq in. gage	4.4	4.4
Blowout pressure of bags, lb/sq in. gage	10.8	10.8
Atmospheric pressure, lb/sq in. gage	14.7	14.7
Vertical velocity at contact, ft/sec	7.5	30.0

TABLE II

SCALE RELATIONSHIPS FOR THE MULTIPLE-AIR-BAG REENTRY VEHICLE

[λ = Scale of model]

Quantity	Full scale	Scale factor	Model
Length	l	λ	λl
Acceleration	a	1	a
Pressure	p	1	p
Area	A	λ^2	$\lambda^2 A$
Weight	W	λ^2	$\lambda^2 W$
Moment of inertia	I	λ^4	$\lambda^4 I$
Time	t	$\sqrt{\lambda}$	$\sqrt{\lambda} t$
Speed	v	$\sqrt{\lambda}$	$\sqrt{\lambda} v$
Force	F	λ^2	$\lambda^2 F$
Volume	V	λ^3	$\lambda^3 V$

TABLE III

TEST DATA OF THE MULTIPLE-AIR-BAG MODEL

[Values converted to full scale]

Attitude, deg	Flight path, deg	Vertical velocity, ft/sec	Horizontal velocity, ft/sec	Acceleration		Time to peak	
				Normal, g	Longitudinal, g	Normal, sec	Longitudinal, sec
0	90	30	0	8.04	2.48	0.136	0.092
0	90	30	0	7.54	2.33	.140	.096
0	90	30	0	8.22	2.48	.136	.104
-15	90	30	0	6.18	3.86	.168	.076
-15	90	30	0	6.18	3.86	.172	.164
15	90	30	0	15.3	1.9, -2.87*	.140	0.13, 0.18
1.5	45	30	30	8.22	2.38	.136	.028
-2	45	30	30	8.78	3.86	.172	.188
-6	45	30	30	7.66	3.52	.164	.136
-6	45	30	30	7.60	3.52	.160	.120
7	45	30	30	10.32	1.98	.156	.156
5	27	30	60	9.1	2.72	.152	.152
-12	27	30	60	7.66	4.16	.192	.204
12	27	30	60	10.6	3.37	.164	.164
20	27	30	60	12.7		.160	

*Acceleration reversal.

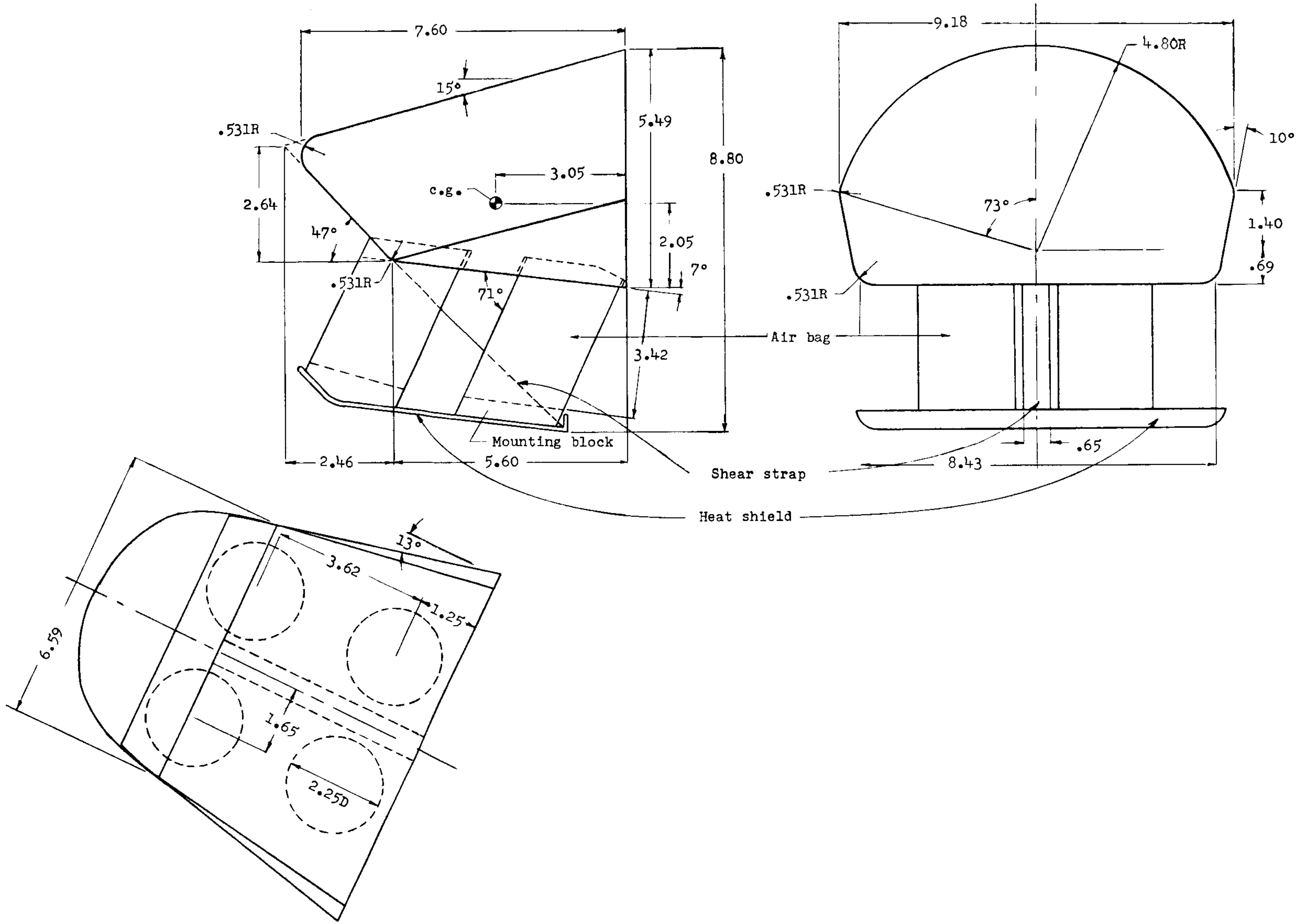
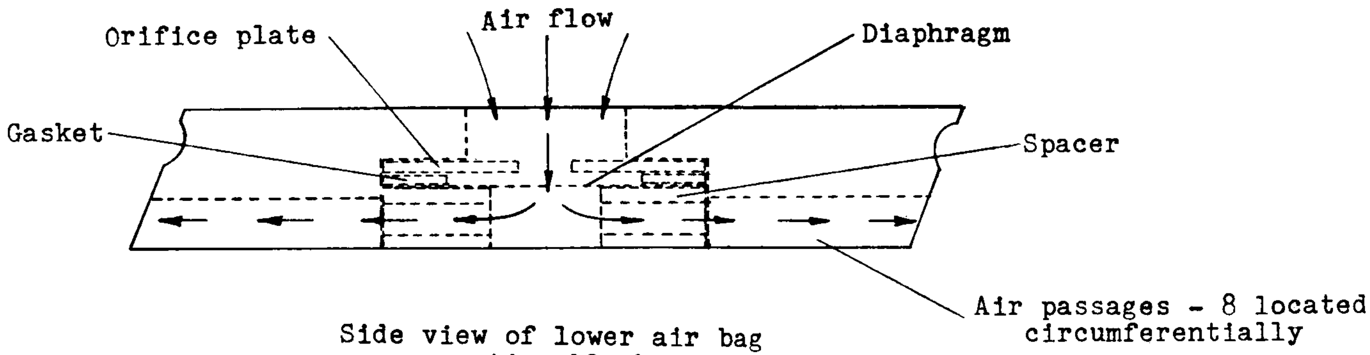
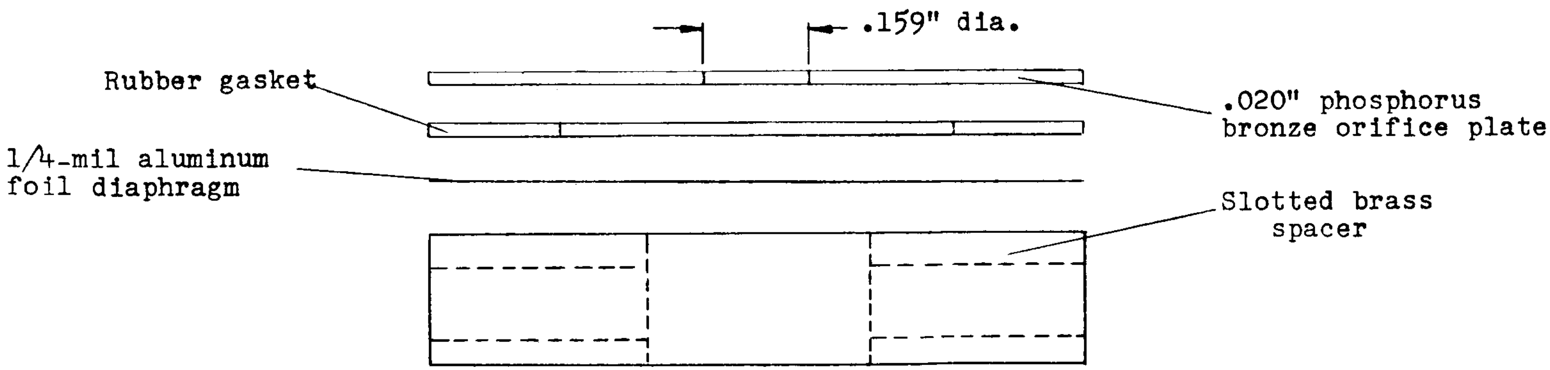


Figure 1.- General arrangement of 1/16-scale dynamic model. (All values are in inches model scale.)



Side view of lower air bag mounting block



Exploded view of orifice plate and diaphragm arrangement

Figure 2.- Sketch showing details of lower air-bag mounting block. (All dimensions are in inches model scale.)

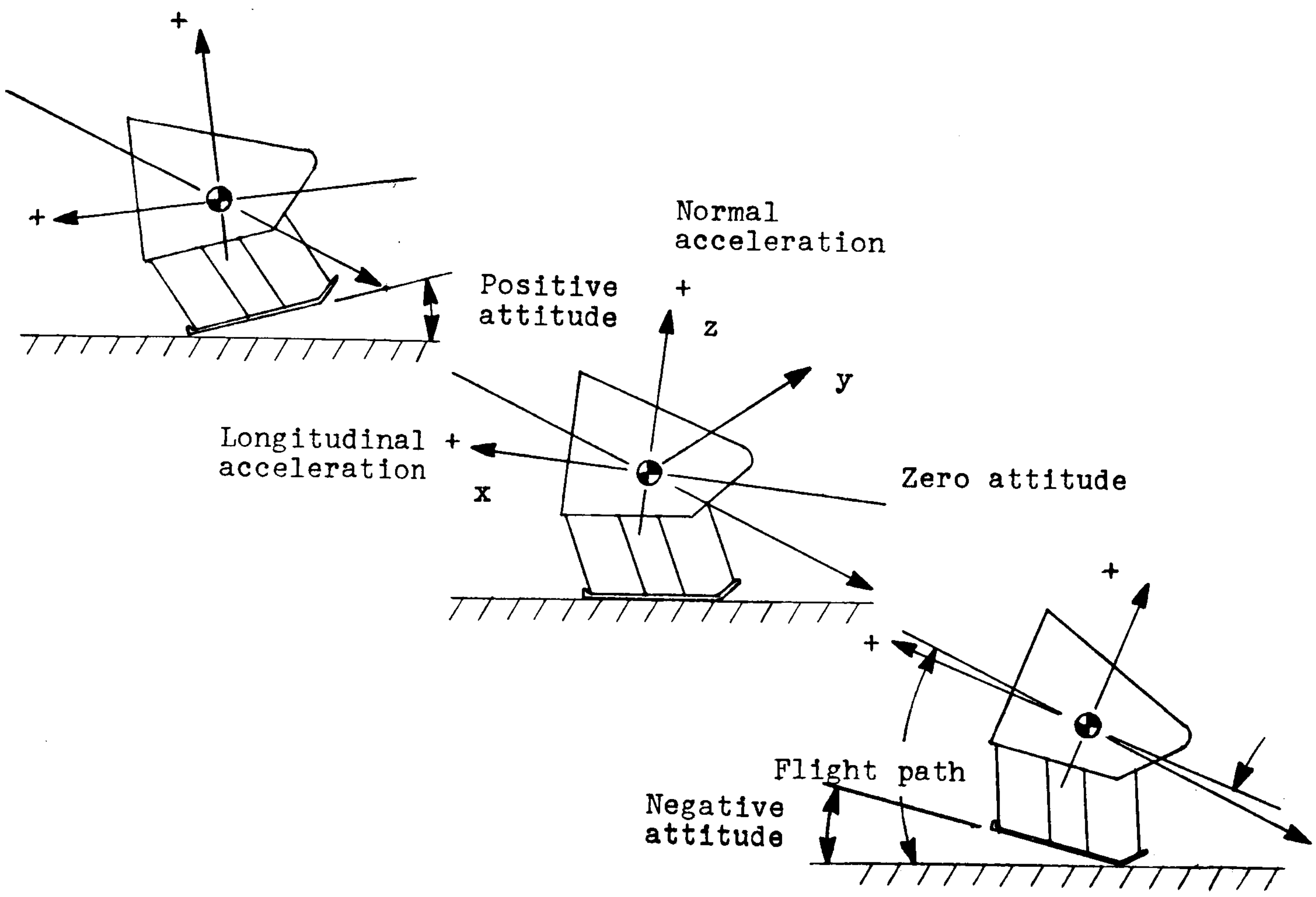
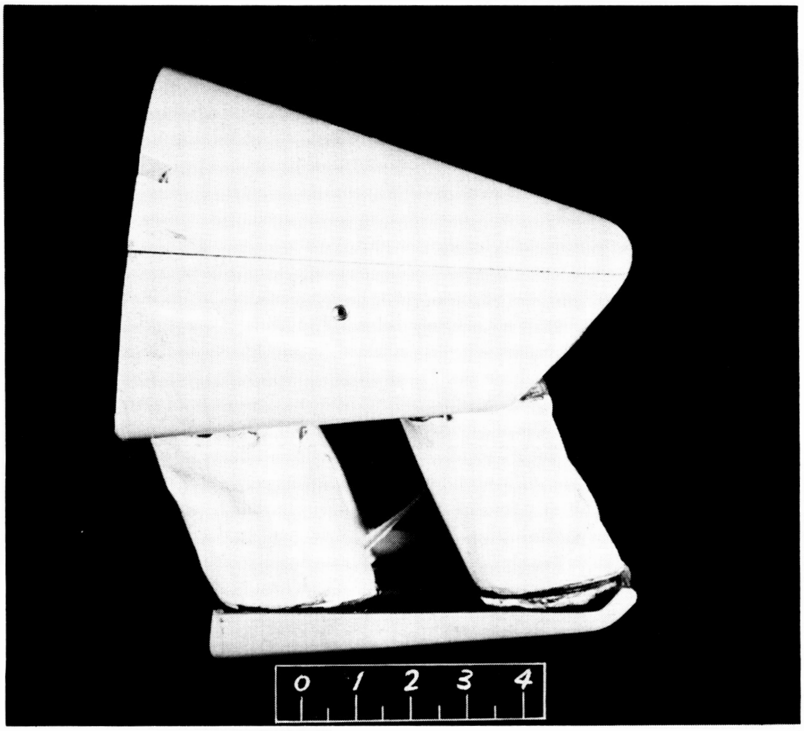


Figure 3.- Sketches identifying acceleration axes, attitudes, and flight path.



Side view

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3/4 front view

L-61-3444

Figure 4.- Photographs of 1/16-scale reentry vehicle.

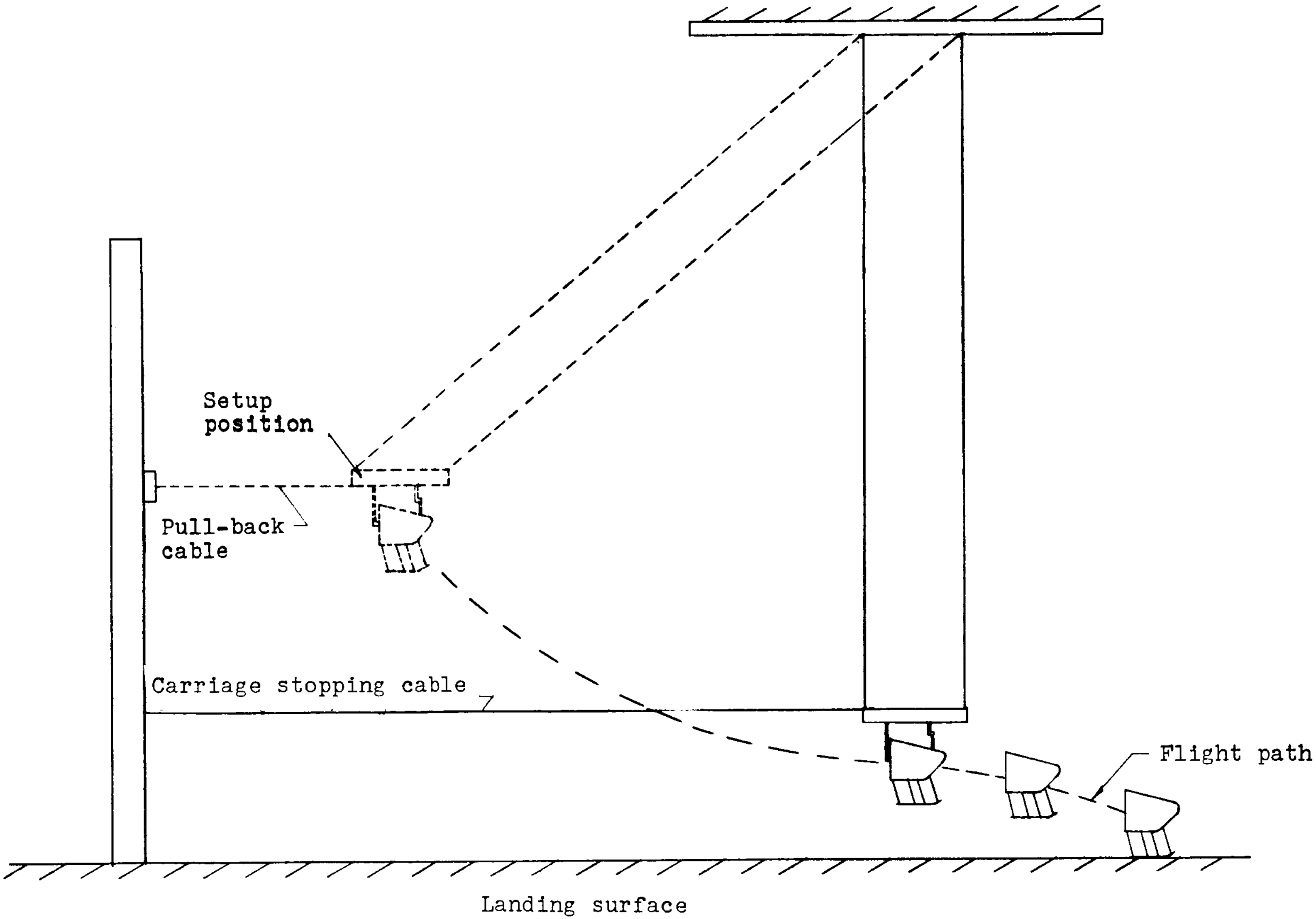
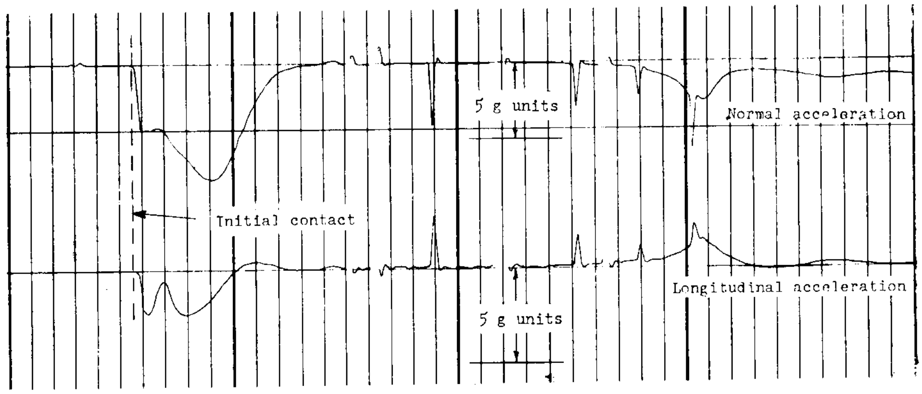
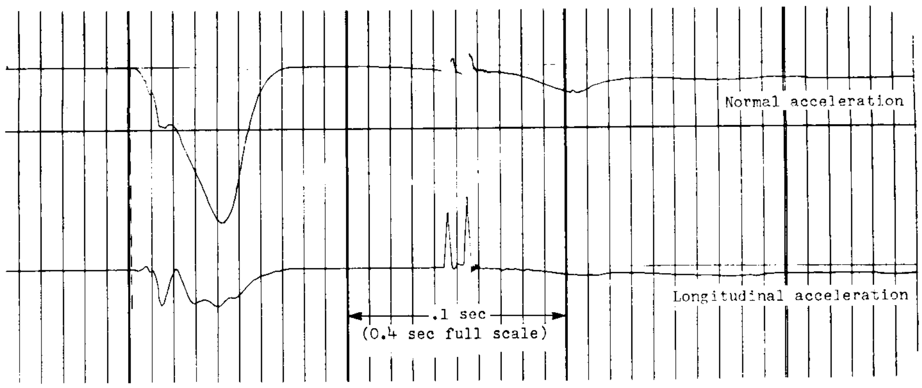


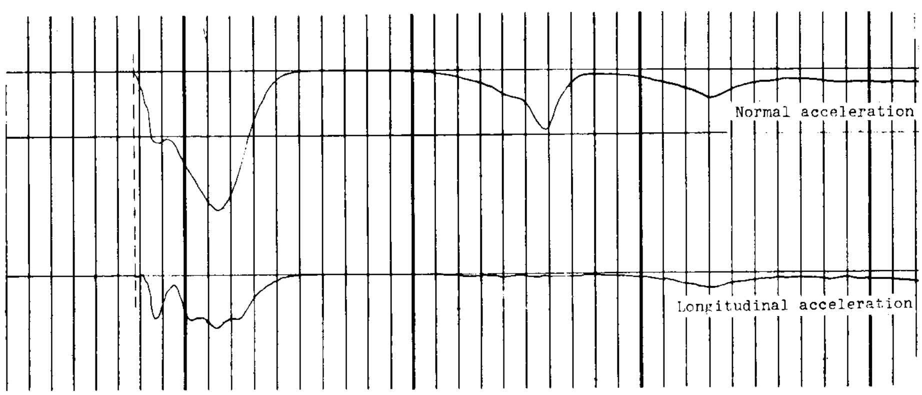
Figure 5.- Sketch of test setup.



(a) Horizontal velocity, 0 ft/sec; landing attitude, 0°.

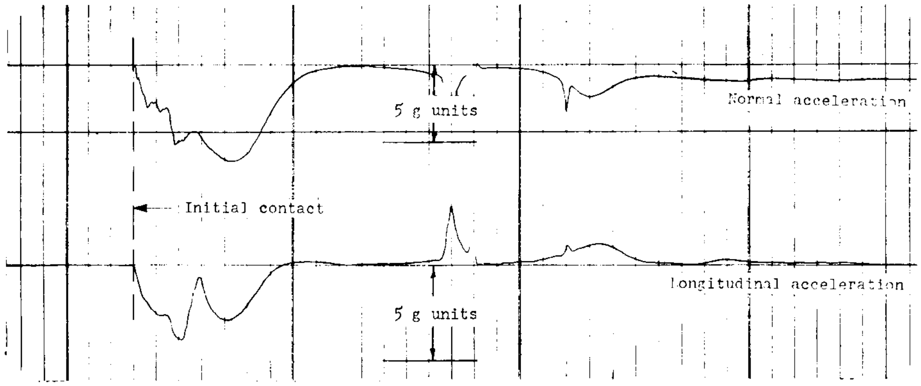


(b) Horizontal velocity, 30 ft/sec; landing attitude, 7°.

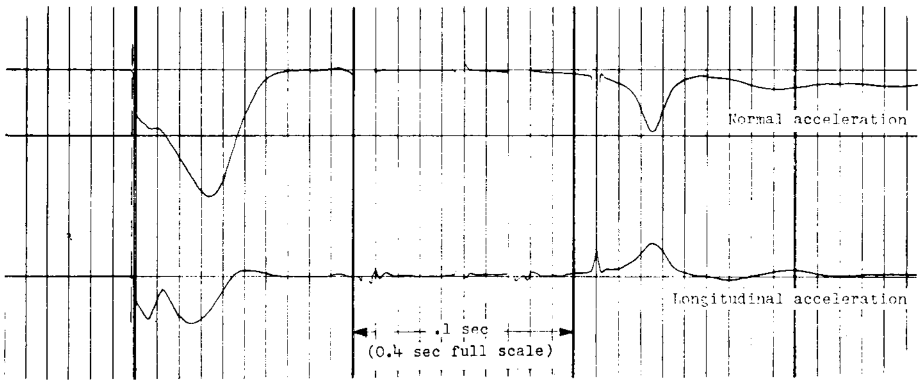


(c) Horizontal velocity, 60 ft/sec; landing attitude, 5°.

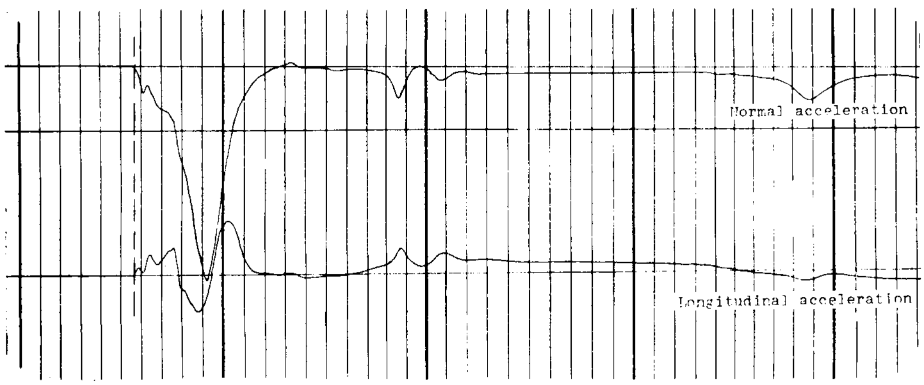
Figure 6.- Typical oscillograph records of normal and longitudinal accelerations showing the effect of horizontal velocity. Vertical velocity, 30 feet per second.



(a) Horizontal velocity, 0 ft/sec; landing attitude, -15°.



(b) Horizontal velocity, 0 ft/sec; landing attitude, 0°.



(c) Horizontal velocity, 0 ft/sec; landing attitude, 15°.

Figure 7.- Typical oscillograph records of normal and longitudinal accelerations showing the effect of landing attitude. Vertical velocity, 30 feet per second.

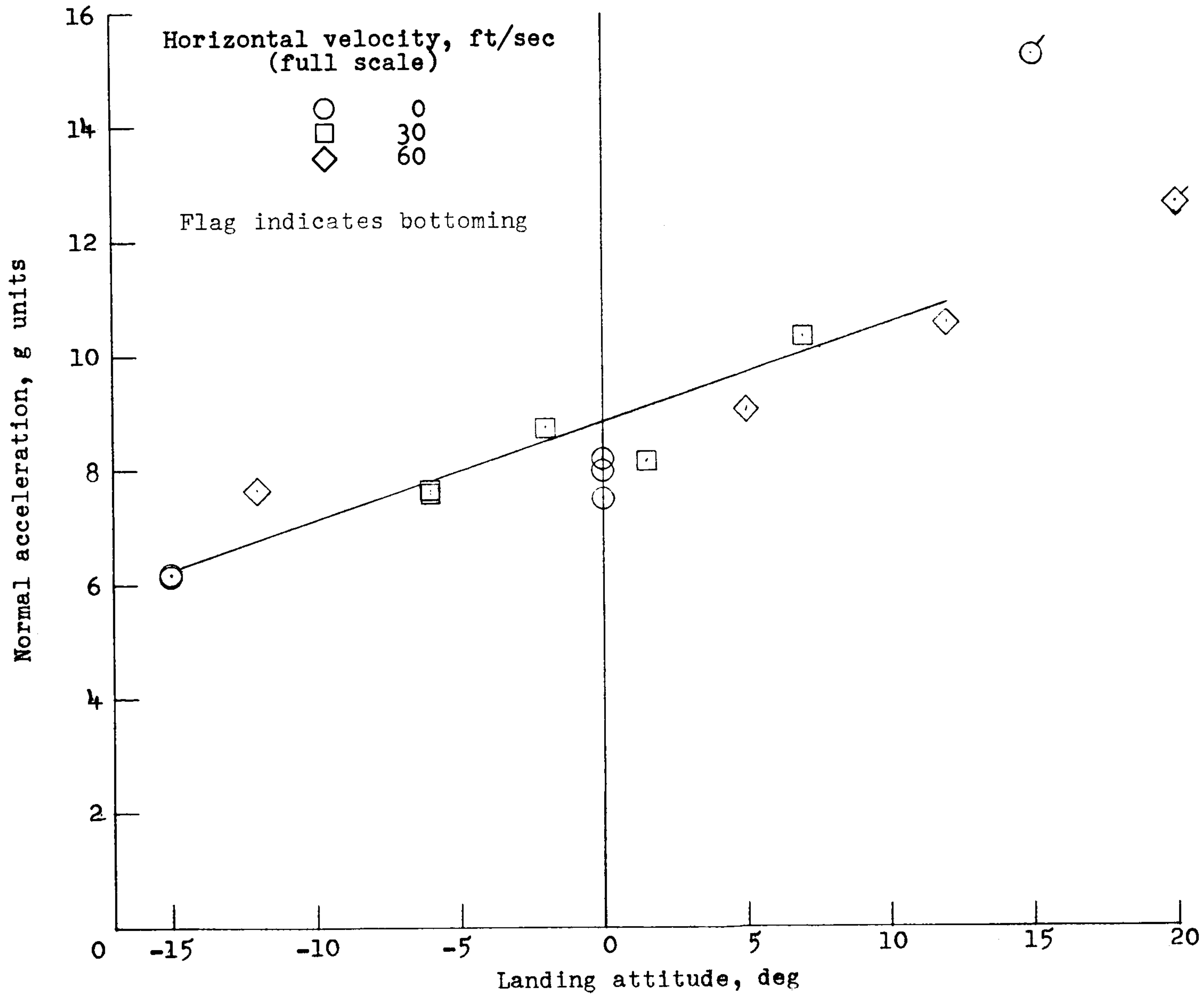


Figure 8.- Maximum normal accelerations as a function of landing attitude for landings on concrete. Vertical velocity, 30 feet per second.

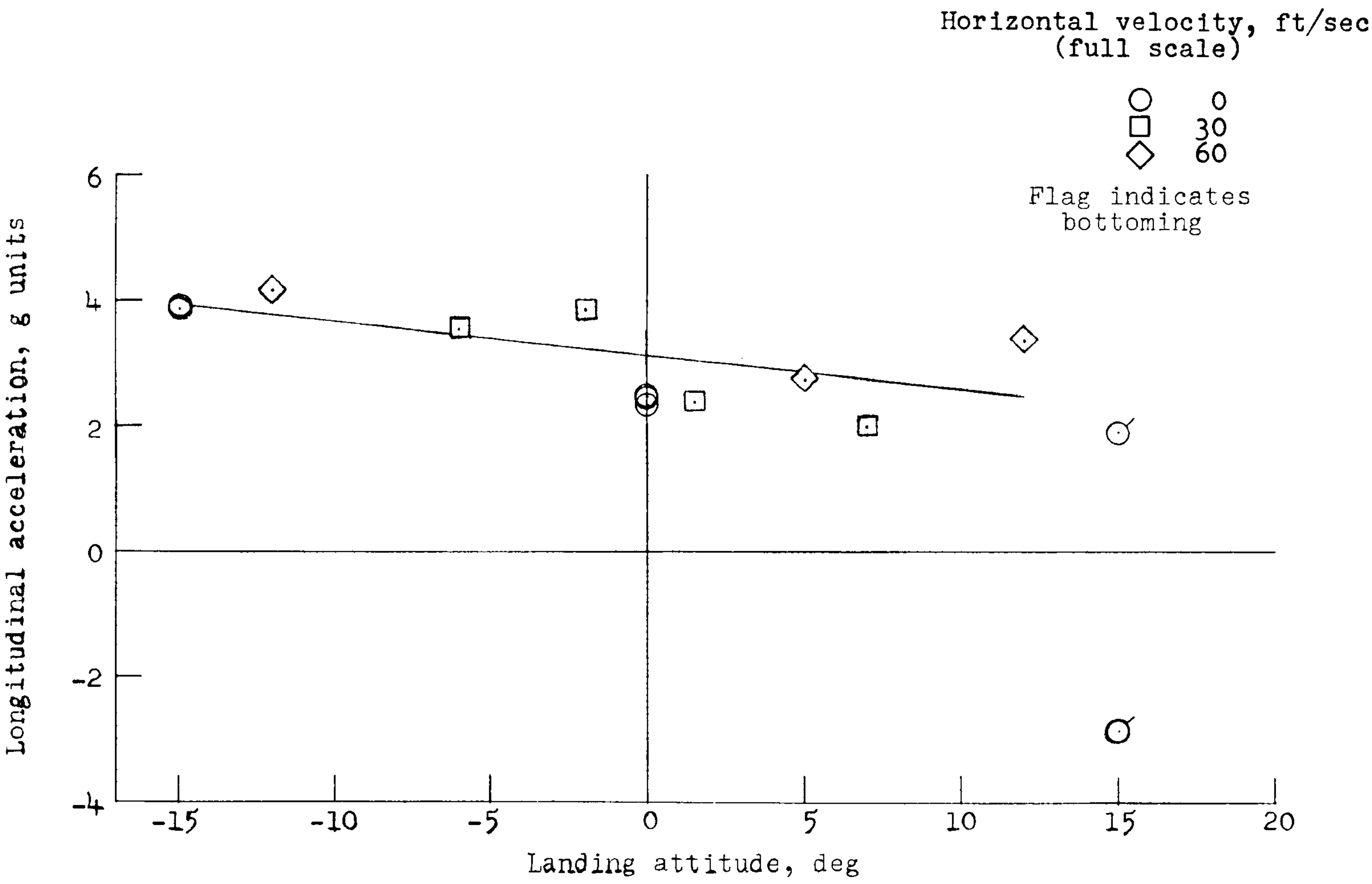


Figure 9.- Maximum longitudinal accelerations as a function of landing attitude for landings on concrete. Vertical velocity, 30 feet per second.

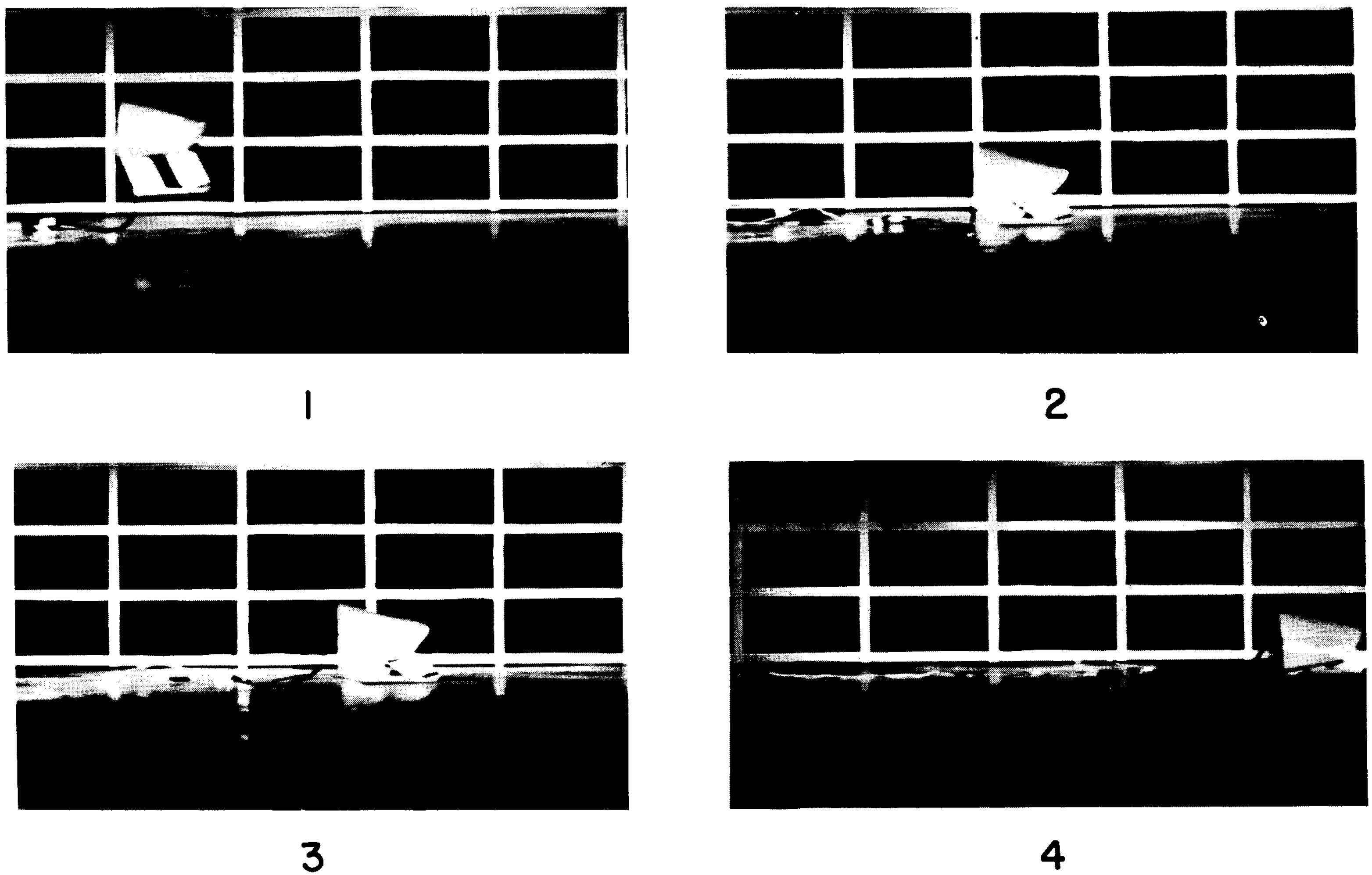


Figure 10.- Typical sequence photographs of multiple-air-bag model landing on concrete. Flight-path angle, 27°; landing attitude, 5°. L-61-4812.1

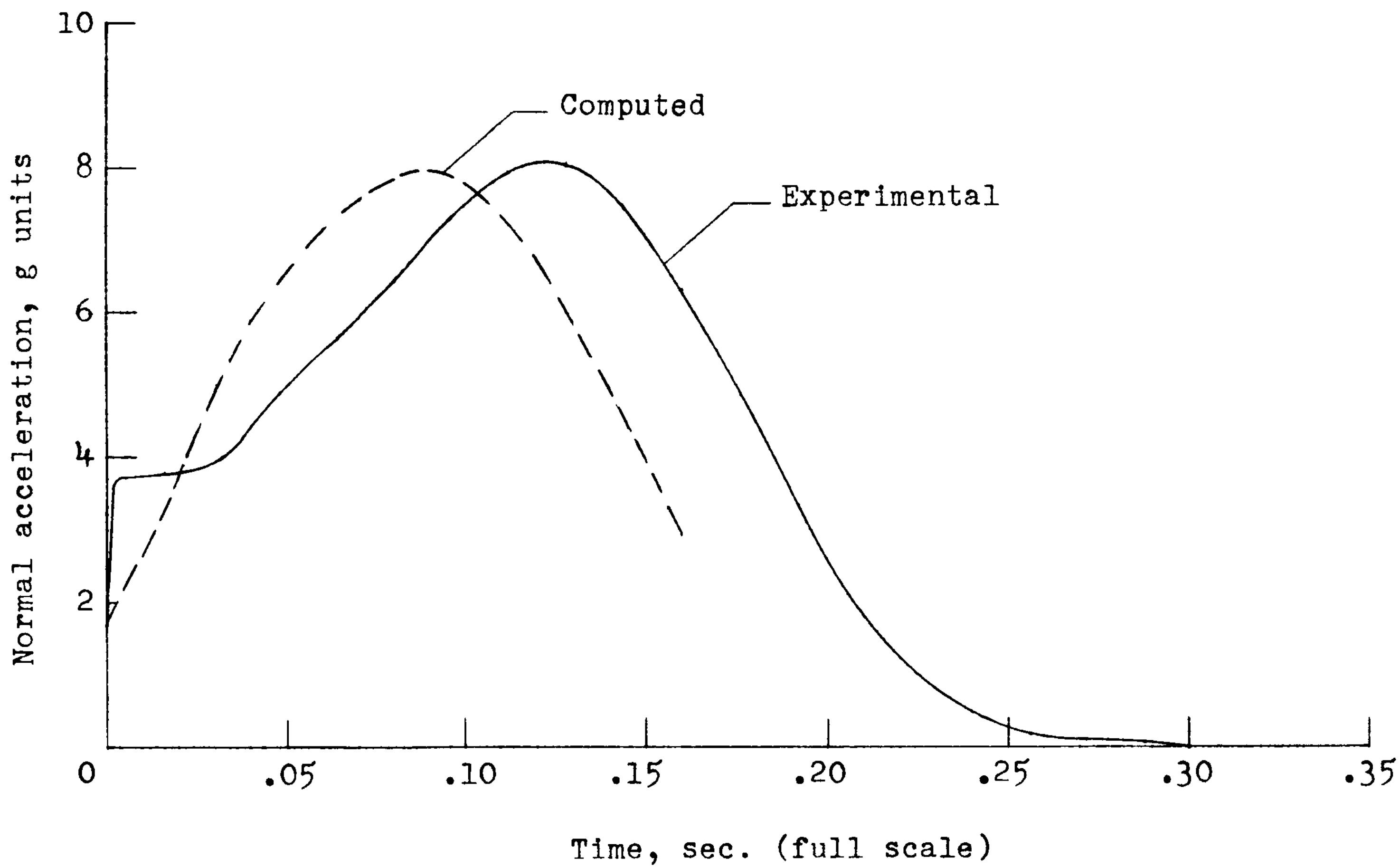


Figure 11.- Acceleration time-history comparison between experimental tests and computed results. Vertical velocity, 30 feet per second; flight-path angle, 90°; landing attitude, 0°.

A motion-picture film supplement (L-785) is available on loan. Requests will be filled in the order received. You will be notified of the approximate date scheduled.

The film $\left(16 \text{ mm}, 3\frac{1}{2} \text{ min, color, silent}\right)$ shows representative model tests at various contact attitude and landing velocities.

Film supplement L-785 is available on request to

Chief, Photographic Division
National Aeronautics and Space Administration
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